Next-Generation Radioisotope Thermoelectric Generator Study

Christopher S. R. Matthes
Jet Propulsion Laboratory,
California Institute of Technology
4800 Oak Grove Dr.
Pasadena, CA 91109
818-354-3255
cmatthes@jpl.nasa.gov

David F. Woerner
Jet Propulsion Laboratory,
California Institute of Technology
4800 Oak Grove Dr.
Pasadena, CA 91109
818-393-2000
david.f.woerner @jpl.nasa.gov

Terry J. Hendricks
Jet Propulsion Laboratory,
California Institute of Technology
4800 Oak Grove Dr.
Pasadena, CA 91109
818-354-4779
terry.j.hendricks@jpl.nasa.gov

Jean-Pierre Fleurial
Jet Propulsion Laboratory,
California Institute of Technology
4800 Oak Grove Dr.
Pasadena, CA 91109
818-354-4144
jean-pierre.fleurial@ jpl.nasa.gov

Knut I. Oxnevad
Jet Propulsion Laboratory,
California Institute of Technology
4800 Oak Grove Dr.
Pasadena, CA 91109
818-393-0675
knut.i.oxnevad.dr@ jpl.nasa.gov

Chadwick D. Barklay
University of Dayton Research Center
300 College Park
Dayton, OH 45469
937-229-3167
chadwick.barklay@ udri.udayton.edu

June F. Zakrajsek
NASA Glenn Research Center
21000 Brookpark Rd.
Cleveland, OH 44135
216-977-7470
june.f.zakrajsek@ nasa.gov

Abstract—**Radioisotope Thermoelectric Generators (RTGs) have been used to power NASA missions of various types throughout the past five decades. The most recent RTG iteration, used for NASA's Mars Science Laboratory, is the Multi-Mission RTG (MMRTG), which is currently the only spaceflight-qualified system available. The U.S. planetary science community has expressed a desire for more power system options to be available to accommodate a range of ambitious future mission concepts across the solar system. Recent advancements in thermoelectric (TE) materials technology have raised a potential for significantly increased efficiency in future RTGs, which helped spur a recent in-depth NASA study of options for future systems. A "next-generation" RTG study was conducted to develop new RTG concepts that could meet the needs of planetary science missions through the 2030s and beyond. A Next-Generation RTG would aim to extend the types of potential NASA missions able to be supported, while fulfilling requirements related to technical risk and schedule. In this study, 21 potential thermoelectric couple configurations were analyzed by considering various high-performance, high-temperature TE materials and segmentation techniques that maximize convertor efficiency and power density. System modularity was explored, and found to be a promising means to offer improved flexibility for NASA mission concepts with varying scope and power requirements. This paper presents the results of the study, demonstrating the viability of developing an updated RTG system design, and defining conceptual system approaches for a new, potentially revolutionary RTG.**

TABLE OF CONTENTS

1. INTRODUCTION

Radioisotope Power Systems (RPS) have supported NASA spaceflight missions for five decades, using reliable and proven technology to power historic achievements throughout our solar system, and beyond. A number of RTG designs and associated TE materials have been employed for various mission types, from planetary probes to landers. At the present time, some future mission concepts are not well matched to the currently available RTG system, the MMRTG. The MMRTG is designed for both vacuum and atmospheric environments. The prior RTG available for deep space missions was the General Purpose Heat Source (GPHS)-RTG, last used for NASA's New Horizons mission, which was launched in 2005. This system yielded higher power levels than the MMRTG, but was only operable in the vacuum of space. The need for a robust and reliable power system able to support a broader scope of future planetary missions has recently prompted the Next-Generation RTG Study[1]. This effort aimed to explore the viability of various system concepts, utilizing current TE technologies, to develop an updated RPS able to fulfill NASA Planetary Science Division (PSD) exploration needs for the next 20 years.

This undertaking drew upon expertise from NASA Glenn Research Center, NASA Goddard Space Flight Center, and NASA Jet Propulsion Laboratory/California Institute of Technology, as well as the Johns Hopkins University Applied Physics Laboratory, the US Department of Energy, and the University of Dayton Research Institute.

The study objective was to deliver a full analysis of the requirements, constraints, and considerations for designing the next RTG system. This analysis was developed with the goal in mind of meeting the needs of the PSD as outlined by the most recent Decadal Survey[2], and expanded with an emphasis on the exploration of Ocean Worlds. A top-down approach was used to develop requirements, based on previously used RTG systems, existing launch vehicles and current spacecraft technology, and intended mission destinations and characteristics provided by PSD. A bottom-up approach was utilized to assess thermoelectric (TE) materials available for use in RPS and the corresponding segmentation optimization for the most efficient couple configuration.

Mission analysis was conducted to determine RTG requirements that would produce a system with maximized value and usefulness to various destinations across the solar system. By examining 63 specific target destinations, from ocean and ice worlds, to gas giants and other bodies within our solar system, potential missions were formulated to specify goals and needs for the implemented power systems. Table 1 shows the specific target categories that comprise the selection, which span a distance range of 0.39 to 44 AU from the sun. A total of 249 mission concepts to explore these various destinations were reviewed, of which there are a number of possible mission types and associated spacecraft that may be employed. The various mission types include flyby; orbiter; atmospheric probe; aerial probes, which includes balloons, fixed-wing aircraft, and helicopters; surface missions, including impact, landers, rovers, and boats; subsurface missions, exploring liquid, soil and regolith, and ice environments; and potential sample return. A goal of the Next-Gen RTG concept would be to accommodate as many of these mission types as possible in order to maximize its usefulness for future applications[3].

Table 1. Target Destinations

Targets	Quantity
Planets	8
Moons	23
Minor planets	3
Dwarf planets	5
Centaurs	5
Asteroids	10
Lagrangian point	1 (L1)
Comets	9

Mission concept-specific requirements were derived from this analysis, which are important for designing and assessing the characteristics of a future RPS. The end of mission (EOM) power needs for the studied missions were found to range from 10 We to over 1000 We; however, the majority would need under 300 We. It was concluded that a generator producing a large amount of power (e.g. > 500 We) would be excessive for most missions, so generator modularity would be a useful feature to accommodate the entire range of power needs. Regarding system lifetime, while the MMRTG has a design life of 17 years, future missions could likely extend up to 20 years in length. The Next-Gen RTG should match the MMRTG lifetime requirement, with a goal to reach a design life of 20-24 years. Of the studied mission concepts, only 20% necessitated operation within an atmosphere, as the MMRTG is designed to support, meaning the vast majority of future missions would prefer a power system to be optimized for operation in the vacuum of space. Following this finding, it makes sense to draw requirements from the GPHS-RTG when considering the characteristics of the Next-Generation RTG. A number of other qualities contribute to the design considerations, including the environmental variables of the target destinations, encountered temperatures, atmospheric pressures, and radiation levels. Mission-specific factors may also prescribe necessary specifications for the RTG, such as the ability to withstand EDL loads and conduct subsurface exploration, for example.

Technological advancement is another factor that can influence the determination of system requirements. Development of a potential "enhanced" MMRTG (eMMRTG) was initiated from a desire to utilize more advanced Skutterudite TE materials for improved efficiency and power output compared to the conventional MMRTG[4]. Likewise, when performing this study, the team considered combining the most relevant TE technology with a highly advantageous design concept. As is also the case with any new technology, risks and development costs for a Next-Gen RTG must be weighted with its value to assess if the investment is warranted. Implementing certain design adjustments such as modularity or TE segmentation may result in excessive uncertainties related to reliability, budget, and schedule.

This paper will first assess and summarize the status of thermoelectric material candidates by providing a background of recent innovations relevant to RPS applications. Next, RTG design concept options will be outlined and analyzed based on their characteristics, strengths, and associated risks. A roadmap for the Next-Gen RTG development will be identified based on the results of this study, and conclusions from this effort will then be presented.

2. THERMOELECTRIC TECHNOLOGY

Historically, RTGs originally employed tellurium-based TE materials such as lead telluride (PbTe), which generally operate at temperatures in the range of 300-800 K. These materials were prone to sublimation, and required RTGs to be sealed with an inert cover gas. Silicon germanium (SiGe) based alloys were later used because of their ability to achieve greater efficiencies and operate at higher temperature ranges of 800-1300 K. Because SiGe has a negligible sublimation rate below 1300 K, RTGs could then be designed to operate in vacuum environments without a cover gas. The MMRTG implemented TAGS-85 with lead telluride TE technology into its couples, but these legacy materials have shown to yield relatively low system-level conversion efficiencies[1]. Scientific research in the area of thermoelectrics aims to advance the effectiveness of these types of materials for use in future energy conversion devices.

A number of notable advancements in TE material development provide significant potential for improved efficiency and power generation in future RTGs. This study evaluated 38 n-type, and 29 p-type materials, with technology readiness spanning from those at a fundamental research level up to flight proven. These candidates included high-temperature thermoelectrics developed by, or in collaboration with, JPL/Caltech under contract by NASA. The selection criteria aimed to use materials that possess a reasonably high figure of merit (ZT > 1) to achieve high conversion efficiencies (≥ 12%) over a large temperature gradient (ΔT > 700K). The figure of merit (eq. 1) is a dimensionless quantity that characterizes the efficiency of a TE material to convert heat into electrical power[5].

$$ZT = \frac{\alpha^2 T}{\rho k} \tag{1}$$

Here, α is the Seebeck coefficient, ρ is the electrical resistivity, and k is the thermal conductivity. These relevant material properties are to remain stable over the operating lifetime of the device. The materials are to also offer low programmatic risk from a technology maturation perspective.

Since the figure of merit of each TE material reaches a maximum at a different temperature, the efficiency of a couple can be significantly improved by concatenating the n- and p-legs of a device into multiple segments of different materials[6]. Figure 1 displays the ZT values for a number of n-type materials, plotted over a temperature range. It can be seen that a particular material may possess the highest ZT within a specific range, while being relatively low at other temperatures. By segmenting the couples, the temperature-integrated average figure of merit of each leg can be increased over a relatively large temperature gradient. In producing selections of couple configurations in this work, different materials were chosen across low (300-473 K), middle (473-873), and high (873-1273) temperature ranges, based on whichever range their peak ZT occurred. From the candidate materials, a total of 21 optimized couple configurations were conceived for further consideration, and arbitrarily named “TC-1” through “TC-21”.

Segmentation increases risk, as each mechanical interface provides an additional likelihood of mismatch between the coefficients of thermal expansion (CTE) for each material, and additional electrical and thermal interfaces with chemical compatibility, diffusion-driven interface degradation, and lifetime impacts on performance and risk. In addition, material degradation performance will differ between segment materials, providing additional levels of risk that must be mitigated. The magnitude of risk varies according to the materials used, and their respective technology readiness levels. This risk must be balanced with the performance qualities of each configuration to select the best candidates for further study. Of the 21 pre-selected couple configurations, the set was reduced to eight recommended for further NASA technology development. Some of these were single-segment couples, and others were double segments.

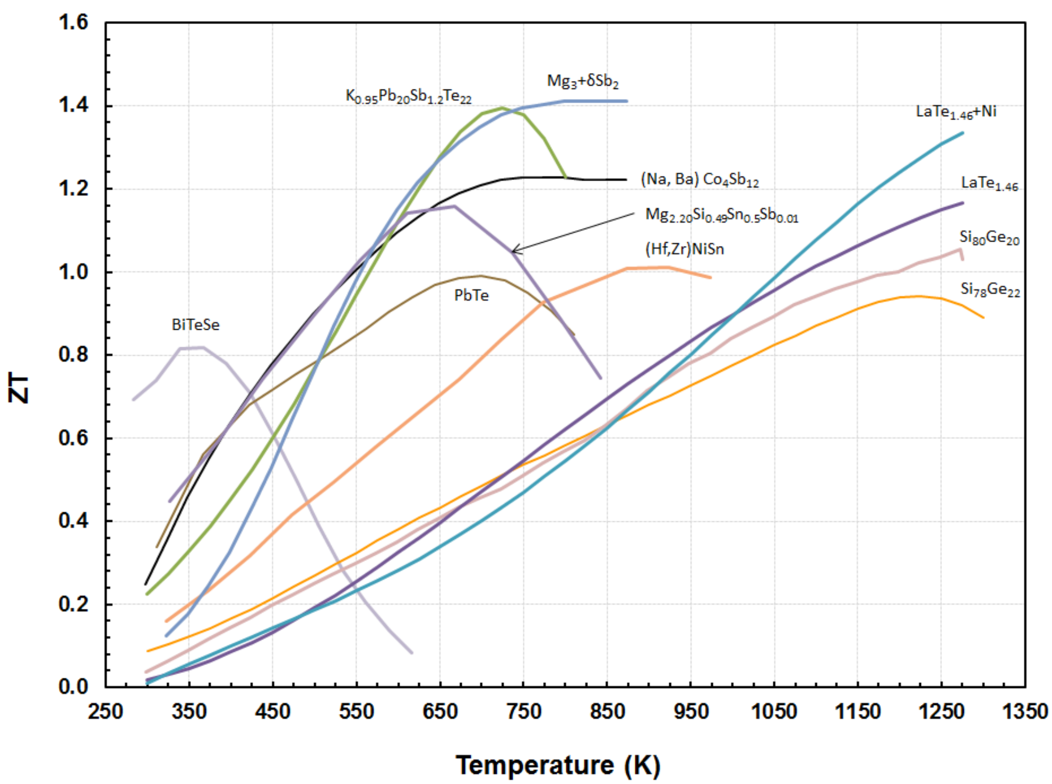


Figure 1. Figure of merit (ZT) for several n-type TE materials across a temperature range

Low-temperature segments were initially considered to harness an overall greater conversion efficiency, but further analysis showed consideration of these alternatives to be no longer viable. It was determined that the risk associated with segmentation and the increased mass penalty was not acceptable relative to the benefit of this option. The eight couple selections were made by assessing the balance between risk and performance, and screening their technology readiness level (TRL). A material's TRL is a quantification of its technology maturity. These selections exhibit relatively high efficiencies ranging from 11.3—16.5%, the ability to operate in either vacuum or argon cover gas environments, low sublimation rates ($\leq 10^{-6}$ g/cm^2/hr), and less than 10% CTE mismatch between the segments. The selected eight configurations offer the potential for notable improvement over the TAGS-85/PbTe couples used in the MMRTG, but flight implementation would require additional research and development efforts. Protective coatings may be needed to suppress sublimation, and challenges related to the material bonding layers may need to be addressed. The segment interfaces will need to exhibit mechanical stability, resistance to material diffusion, CTE compliance, and the necessary thermal and electrical conductance properties for effective operation. All these development efforts, leading to a final couple selection, will be critically related to decisions regarding the system concept design.

3. RTG CONCEPTS

The Next-Generation RTG aims to achieve maximum mission adaptability within reasonable limits of development risk and cost. Several design concepts, using the TE multicouple, were considered to assess this balance between usefulness and risk. A number of architectural trades were evaluated based on characteristics of the GPHS-RTG and MMRTG, as well as the needs for future mission concepts specified by PSD. Critical RTG design characteristics and high-level requirements were identified in this process. Final couple selection among those referenced in Section 2 will likely depend significantly on final concept design decisions resulting from system trade studies. These trades included an RTG for vacuum-only operation to eliminate the need to support a cover gas, lowering mass, and increasing the specific power. Alternately, a hybrid RTG for vacuum and atmosphere operation would be optimal for Mars and Titan mission concepts, while maximizing utility across the solar system. Cold-side thermal dissipation sub-systems for the RTG must provide cold-side temperatures that do not interfere with other equipment or sensitive environments, but this can require large heat-rejector fins that dramatically increase the required RTG mass. Finally, modularity of the RTG system, a key design characteristic, allows missions to optimize their power system selection for individual power needs, rather than a "one size fits all" solution.

Three potential design concepts were selected based on these trade studies. First, the Segmented RTG (SRTG) refers to the TE couple (TEC) design, where segmentation techniques are used to improve conversion efficiency, as explained in the previous section. This RTG design would be a single size, built around 16 Step 2 GPHS units, and could only be operated in vacuum. It most closely resembles the GPHS-RTG, which used an 18 Step 0 GPHS architecture[1]. The design considerations and system requirements for this option are largely determined by the TE materials associated with the set of eight selected TEC configurations. These materials provide the operating temperature range requirements. The estimated SRTG beginning of life (BOL) power output is 590 We, with an estimated mass of 62 kg. This compares to a GPHS-RTG power output of about 290 We, with a mass of 57 kg. The risk associated with the SRTG relates to CTE mismatch between segment interfaces and other material interface compliance and degradation challenges, as previously discussed.

The second concept that emerged is the Segmented-Modular RTG (SMRTG). Like the SRTG, the SMRTG would use TEC segmentation to improve energy conversion efficiency. Modularity is the defining feature of this variant, which allows for interchangeability at the system level. This feature has many notable benefits, which includes increased flexibility in the spacecraft design relative to power system accommodation. There are a number of means by which to achieve modularity, such as implementing a "building block" design that consists of several identical or differently sized modules able to be connected together through a mechanical interface. The risk for this approach was deemed too high, as each mating point can contribute to leakage that would be highly unpredictable. Instead, it was determined that each SMRTG size variation would be designed with a unique housing in order to eliminate many risk associated with interface leak paths. The voltage requirement is the next consideration determining the RTG sizing. Typically, NASA spacecraft power busses have been designed to operate in the range of 22 to 36 V. For TECs electrically configured in series, the voltage will be proportional to the number of couples in the circuit. A series-parallel cross-strapped circuitry has been employed in previous RTGs as a means to ensure fault tolerance and improve reliability, which also doubles the required number of TECs built into the generator. A two-GPHS unit was determined to be the smallest SMRTG variant capable of supporting the necessary number of TECs to meet the specified voltage requirement. This basic architecture would be electrically integrated in parallel for larger variants, such that the smallest (two-GPHS) variant determines the output voltage. Multicouples, a collection of eight TECs within a single package, are used as a means to increase the quantity of TECs within the available space. Figure 2 shows a concept illustration of the basic anatomy of a two-GPHS SMRTG unit. Here, a segmented multicouple is represented, which is located within the housing with radiator fins, as shown. A collection of 52 multicouples would be wired in a series-parallel circuit to compose a ring surrounding the GPHS pair, producing an output of 34 V. With a minimum size of two GPHS, eight SMRTG sizes (or configurations) are possible using 2, 4, 6, 8, 10, 12, 14, or 16 GPHS. The 16-GPHS configuration would match the power output and mass specifications of the SRTG.

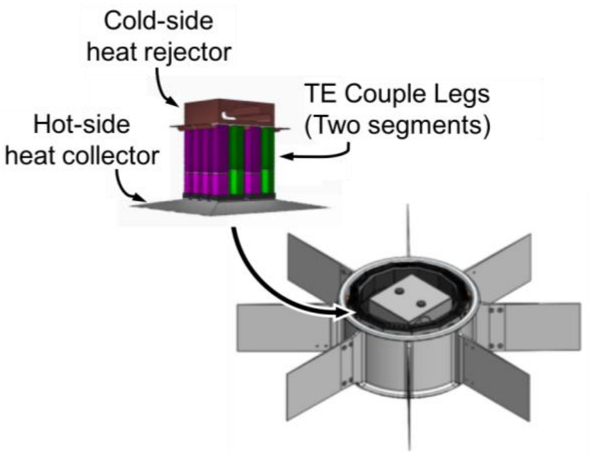


Figure 2. A two-unit SMRTG concept without closeouts. Segmented multicouples surround a stack of two GPHS within the housing, as shown. For illustration only, not representative of a complete design.

Lastly, hybridization was explored to allow for the Next-Generation RTG to be capable of operating in both vacuum and atmospheric environments. The Hybrid-Segmented-Modular RTG (HSMRTG) would have the ability to support all mission types and destinations considered in this study. This feature does not impose any significant mass increase compared with the SMRTG; however, it is a substantial contributor to risk, as hybridization would require hermetic vacuum sealing that must be maintained throughout the 17+ year design life. At this point it is not clear what resources or manufacturing capabilities would be needed to fabricate and certify this design feature. In the case where hybridization is not selected, the MMRTG can provide support to missions requiring operation in an atmosphere while the Next-Generation RTG would support vacuum-only missions.

Cold RTG versions of the SRTG, SMRTG, and HSMRTG were also considered. This form of RTG concept is designed such that the cold-side temperature is much lower than is typical (for example, as low as ~80°C). In this case, TECs would be segmented in order to take advantage of the larger thermal gradient and produce a higher power output. TEC materials may be strategically selected for the lower temperatures in order to raise the average ZT of the couple. To facilitate this larger temperature differential, the heat rejector fins would need to be significantly larger than the standard options, spanning up to 2 m tip-to-tip. The larger size would prevent these RTG concepts from complying with the Department of Energy (DOE) shipping container size requirements. This configuration would also result in a significant mass penalty, causing such RTGs to become unacceptably massive. Additional TEC segmentation also introduces extra risk as discussed previously.

Specific power refers to an RTG's power output as a ratio to its mass. The SMRTG and HSMRTG concepts provide nearly identical power output and mass for the respective size options at the fidelity at which they were modeled, and the SRTG corresponds with the 16-GPHS version of these selections. Considering all size options and TEC selections, there were 64 generator candidates in total to evaluate. Figure 3 displays the BOL specific power estimates, in W/kg, for the various size options of each TEC selection. The eight previously mentioned couple selections are labeled as "TC-" followed by the respective couple number from the original 21 conceived configurations. The BOL specific powers of the MMRTG, eMMRTG, and GPHS-RTG are also displayed in the figure for comparison. It can be seen that all options exceed the specific power of both the MMRTG and eMMRTG, with the exception of one option. This improvement is attributed to notably improved power outputs, which translates to significant fuel savings. That is, in some cases the power output using four GPHS may exceed that of the GPHS-RTG using 18 GPHS, resulting in a 78% fuel savings. Additionally, the greater power output of the larger size configurations may eliminate the need for multiple RTGs on certain missions, saving significant mass and fuel resources. It can be noted that the specific power of the generator increases relative to the number of GPHS used, demonstrating that a single larger RTG is more mass efficient than multiple smaller RTGs cumulatively achieving a comparable power level.

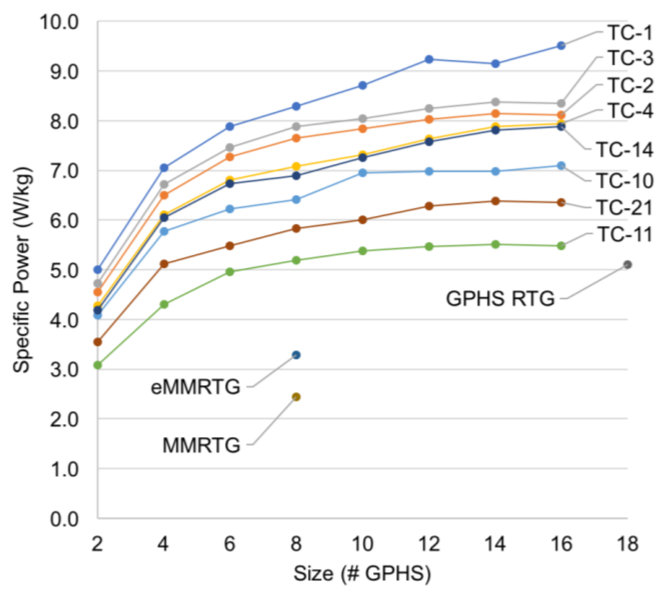


Figure 3. BOL Specific Power of each size of RTG, utilizing the 8 TEC selections. Legacy systems are also displayed for comparison.

A comparison of previous RTG versions to the requirements for the largest (16-GPHS) Next-Generation RTG is provided in Table 2. Here it can be seen that notable BOL and end of mission (EOM) power improvements are expected compared to previous versions, with over 70% greater BOL output than the GPHS-RTG, attributed largely to updated TE technology. Mass and size are comparable to the GPHS-

RTG specifications, while using less fuel. A comparison of the Next-Generation RTG with the MMRTG and its potential updated counterpart, the eMMRTG, shows notably greater power output capabilities with equivalent fuel resources. The power degradation rate requirement was chosen for this study to be 1.9%, which corresponds to the GPHS-RTG requirement, and is significantly lower than the MMRTG degradation level. Future research and development will strive to confirm the lower degradation rates envisioned for these eight newer TE material combinations.

Table 2. Comparison of RTG Specifications with Next-Generation 16-GPHS Concept. Values are approximate.

	MM-RTG	**eMM-RTG***	**GPHS - RTG**	**Next-Gen***
Power, BOL (W)	110	150	290	500
Power, EOM (W)	55	91	213	362
Design Life (yrs)	17	17	18	17
Degradation rate	4.8%	2.5%	1.9%	1.9%
# GPHS	16	16	18	16
Length (m)	0.69	0.69	1.14	1.04
Mass (kg)	45	44	57	62

* Predicted values

Modularity is shown to offer substantial value to the RTG design, in its ability to offer options that can better meet specific mission requirements across a wider spectrum of potential missions. These options translate to both fuel and mass savings, allowing RTGs to be a more viable option for future mission concepts of all types. These valuable attributes outweigh the apparently lower risk of a fixed-size design such as the SRTG. Hybridization may be an advantageous design feature, but further consideration of its viability must be performed to assess its value relative to the perceived additional risk. This perceived risk results from uncertainty in the design characteristics, where the thermoelectric cavities may require vacuum sealing to be maintained over its lifetime. In addition, the architecture of the generator is expected to possess notable differences from the MMRTG, which presents manufacturing challenges and reliability risks.

4. ROADMAP

After this study was completed and shared with NASA's PSD, top-level driving requirements were agreed upon that would anchor the technology maturation implementation efforts. The following are the top-level driving requirements for the Next-Gen RTG system:

- Vacuum-only system
- Modular system
- 16 GPHSs (largest RTG variant)
- P_{BOL} = 400-500 W_e (largest RTG variant)
- Mass goal of < 60 kg (largest RTG variant)
- Degradation rate < 1.9 %
- System to be designed to be upgraded with new TCs as technology matures

With these notional requirements, the RPS Program and its TE Technology Development Project developed an implementation roadmap. This plan has two main efforts:

1) Increasing the readiness of the eight selected TE couple configurations
2) A procurement effort to engage industry for the final technology maturation process.

The first effort will identify and mature selected TE materials and technologies that can be considered for generator development. This effort will include testing and evaluation of materials, development, testing and evaluation of manufactured coupons and TECs, and potentially other related TEC risk mitigation activities, such as coatings, thermal and electrical interfaces, and insulation.

The second effort, involving industry, is planned to take place in two phases. The first phase would be to request input from industry describing their current capabilities and potential approaches that could lead to a future system that would meet the top-level driving requirements. Once this information is collected, NASA may release a procurement in the second phase to solicit vendors to develop system concepts and the associated technology maturation efforts.

At the end of the envisioned contract period, the technologies developed within the context of the system concepts would be evaluated for technology maturity, and risks to future system development. If these risks are deemed reasonable, a decision to proceed with the development of a Next-Generation RTG could be made. At that time, NASA would likely request that DOE release a procurement to develop a Next-Generation RTG. This would initiate the engineering and design effort that would result in the development of an engineering unit and qualification unit. NASA could then work with the DOE to produce flight-ready Next-Gen RTGs that would be ready to support future planetary missions.

5. CONCLUSIONS

Only one type of RTG is currently available to support an ambitious set of future missions being considered by NASA's Planetary Science Division. A study of Next-Generation RTG concepts completed in the last year has identified several viable and achievable concepts that could fill the needs of the planetary science community. A majority of the many potential science missions studied as part of this effort could be achieved using these new RTG concepts paired with high-performance TE materials. With NASA's plan to engage industry and make the highest TRL technologies available to system developers, NASA would be well positioned to deliver new, more powerful, more efficient RTGs through the 2020s.

ACKNOWLEDGEMENT

The research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

The information in this paper about future RPS is pre-decisional and is provided for planning and discussion purposes only.

REFERENCES

[1] Woerner, D., et al. "Next-Generation Radioisotope Thermoelectric Generator Study Final Report." JPL D-99657, NASA Radioisotope Power Subsystem Program, Jet Propulsion Laboratory, California Institute of Technology, 2017.

[2] Space Studies Board and National Research Council. (2012). *Vision and voyages for planetary science in the decade 2013-2022*. National Academies Press.

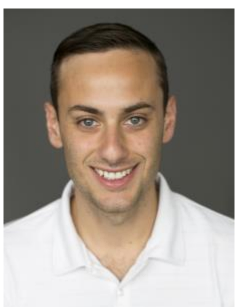
[3] Woerner, D. F. (2017). Next-Generation RTGs for NASA. In *15th International Energy Conversion Engineering Conference* (p. 4612)

[4] Woerner, D. (2016). A Progress Report on the eMMRTG. *Journal of Electronic Materials*, *45*(3), 1278-1283.

[5] Rowe, D. M. (Ed.). (2005). *Thermoelectrics handbook: macro to nano*. CRC press.

[6] Hadjistassou, C., Kyriakides, E., & Georgiou, J. (2013). Designing high efficiency segmented thermoelectric generators. *Energy conversion and management*, *66*, 165-172.

BIOGRAPHY



Christopher S. R. Matthes *received a Ph.D. in Aerospace Engineering from UCLA in 2016. He also has a M.S. from UCLA and a B.S. from Michigan State University, both in Mechanical Engineering. His thesis focused on material surface evolution in electric propulsion devices. Dr. Matthes is currently a mechanical engineer working in thermal energy applications and systems at NASA Jet Propulsion Laboratory, focusing primarily on radioisotope power systems. He also holds a lecturer position at UCLA, where he teaches Mechanical and Aerospace Engineering Laboratory.*

David F. Woerner *has more than 30 years' experience as a systems engineer and manager at JPL including as the MMRTG Office Manager for the Mars Science Laboratory mission. He is presently leading the engineering of an enhanced MMRTG and is the RTG Integration Manager and Deputy Manager of System Formulation and Mission Integration for NASA's Radioisotope Power System Program. Woerner has worked at JPL on such missions as Galileo, Cassini, Magellan, Mars Pathfinder, and MSL. He was the Chief Engineer of the avionics for the Mars Pathfinder mission that successfully landed on Mars on July 4, 1996. He is the Chair of the Board of Directors for the IEEE Aerospace Conferences. He has won numerous NASA awards including earning NASA's Exceptional Service and Exceptional Achievement Medals.*

Terry J. Hendricks *is currently a Technical Group Supervisor, Project Manager, and ASME Fellow at NASA Jet Propulsion Laboratory, responsible for managing NASA-JPL radioisotope power system projects. Dr. Hendricks received his Ph.D. and Master of Science in Engineering from the University of Texas at Austin and Bachelor of Science in Physics from the University of Massachusetts at Lowell. He has over 35 years of professional experience in thermal & fluid systems, energy recovery, energy conversion and energy storage systems, terrestrial and spacecraft power systems, micro electro-mechanical systems, and project management. He was previously an Energy Recovery Program Director at Battelle Memorial Institute, Columbus, OH, and a Senior Program Manager at the U.S. DOE Pacific Northwest National Laboratory (PNNL) in Richland, WA and Corvallis, OR from 2005-2013, where he managed and led U.S. DOE and U.S. Army programs in hybrid power system development, automotive and industrial waste energy recovery, military energy recovery and power system development, and advanced nano-scale heat transfer. He was also Field Program Manager and the Power & Propulsion Task Leader in the Center for Transportation Technologies and Systems at the U.S. DOE National Renewable Energy Laboratory in the early 2000's, where he managed and led heavy vehicle hybrid electric technology programs, thermal management projects, and power system development. Dr. Hendricks has authored or co-authored more than 85 publications, 2 invited book chapters and holds 9 patents. He is a registered Professional Engineer in the states of California and Texas.*

Jean-Pierre Fleurial *is a Senior Research Scientist at the Jet Propulsion Laboratory with nearly 30 years of experience in solid-state energy conversion R&D. He holds a Ph.D. in Materials Science from the National Polytechnic Institute of Lorraine, France, as well as a Professional Engineering Degree from the School of Mines, France. He has achieved international* *recognition in his field as a leader in the research and development of novel materials and devices for thermoelectric energy conversion, in particular for high temperature power generation applications, including waste heat recovery systems and next generation radioisotope and fission space power systems. Dr. Fleurial currently manages JPL's Thermal Energy Conversion Research & Advancement Group and he is the Thermoelectric Technology Development Project Manager for NASA SMD's Radioisotope Power Systems Program.*

***Knut I. Oxnevad** works at the Jet Propulsion Laboratory (JPL), providing management and systems engineering support to the Thermoelectric Technology Development Program (TTDP). He also serves as a resident RTG expert on JPL's development teams. Prior to this, he, over a period of 20 years, led development teams at JPL and in the oil & gas industry. In the oil & gas industry, he supported well planning, field development, and platform modifications efforts. At JPL, his teams performed advanced studies of space payloads, satellites, and surface/subsurface systems, including for rover and lander missions beyond 2010 for Mars, the Moon and other celestial bodies, as well as the SMAP and Aquarius Earth orbiters. During this time, he also chaired the New Design Paradigms Workshops, and ran the Design Process Improvement (DPI) Project within the NASA Engineering Training (NET) office. Dr. Oxnevad received his Ph.D. from Old Dominion University, Norfolk, VA in 1996 and is a graduate of International Space University.*

***Chadwick D. Barklay** is responsible for leading the Advanced High-Temperature Materials Group at the University of Dayton Research Institute (UDRI), which is composed of scientists, engineers, and technicians who conduct cutting edge sponsored material based research and development for various sponsors including DOE, NASA, DOD and a wide range of industrial partners. Dr. Barklay has over twenty-five (25) years of experience in the assembly, testing, and transportation of Radioisotope Power System (RPS) units. Additionally, Dr. Barklay has participated on a number of formal programmatic review committees for DOE and NASA on a broad range of technical areas.*

***June F. Zakrajsek** has over 20 years of aerospace systems development, research and project management experience. She has led internal discipline teams for space systems health management, ISS power systems analysis, and Biotechnology. She has worked as a project manager in the areas of health management, systems engineering and analysis, propulsion system development, Orion Crew Module and Test & Verification, and Radioisotope Power Systems. Currently June serves as the Program System Formulation and Mission Integration Manager for NASA's Radioisotope Power Systems Program. This area is responsible to develop and maintain the implementation strategy for the Program by managing mission and systems analysis functions, integration of new technology into generators, and interfaces with potential missions considering utilizing Radioisotope Power Systems. She holds a Masters in Biomedical Engineering from Case Western Reserve University and Masters and Bachelors in Mechanical Engineering.*